INFLUENCE OF THERMAL PROPERTIES OF WALL DEPOSITS ON
PERFORMANCE OF P.F. FIRED BOILER COMBUSTION CHAMBERS

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1.0 INTRODUCTION

The build-up of ash deposit layers on tube walls and superheaters in dry bottom p.f. boiler combustion chambers not only deteriorates furnace and overall boiler efficiency, but increases the temperature level in furnace and convective passages and aggravates existing deposit problems. This can finally lead to expensive outages when deposit formation cannot be controlled by soot blowing alone. Since errors in furnace design with respect to slagging and fouling or wrong estimation of impact of fuel conversion on deposit formation are so costly in large boilers, there is considerable financial incentive to develop analytical methods in order to predict furnace performance for a wide range of coal types and operating conditions. It is clear that such methods must take quantitatively into account, among other things, the thermal properties of ash deposits.

The properties which determine heat transfer through a deposit layer of given thickness are thermal conductivity, emissivity, and absorptivity. The current paper presents results from various studies carried out by the authors at Energy and Environmental Research Corporation (EER) to show the sensitivity of overall furnace performance, local temperature and heat flux distributions on the properties of deposits in large p.f. fired furnaces.

2.0 PARAMETRIC STUDY OF OVERALL FURNACE PERFORMANCE

The most important parameters for overall furnace heat absorption are the adiabatic flame temperature, the firing density per heat sink area, the emissivity of the furnace volume, temperature and emissivity of the heat sinks and the flow and heat release patterns. Figure 1 shows how these quantities are related in a complex manner to each other, to fuel characteristics and to operating and boundary conditions of the furnace. Some of the relationships of Figure 1 were approximately quantified utilizing a simple well-stirred furnace model (1) which assumed transport of grey radiation. Two important results for furnace performance with respect to formation of deposits are shown in Figures 2 and 3, in which furnace efficiencies η_f,

$$\eta_f \equiv 1 - \frac{\dot{M}_o \; c_p \Big|_{T_o}^{T_{ex}} (T_{ex} - T_o)}{\dot{Q}_o} \qquad 1)$$

are plotted over furnace height L with surface temparatures T_w of deposits and surface emissivities ε_w as parameters. The calculations were carried out for a rectangular furnace box of width L/3. Other input parameters are listed in the Figures. The grey absorption coefficient K_a of 0.1 1/m used in the examples corresponds to an emissivity ε_f = 0.55 for a furnace volume with a height of L = 30m. The effect of deposit surface temperature T_w on furnace efficiency η_f is considerable for values larger than 700 K (Fig. 2). For instance a furnace efficiency of 0.40 (corresponding to T_{ex} = 1440 K according to Equation 1) was obtained for T_w = 700 K (see Section 3 and 4). The L must be increased by 16.5m or 53% of the original height with clean walls to achieve the same furnace efficiency for a furnace with wall deposit of surface temperature 1300 K.* The impact of wall temperature on η_f will be even stronger for adiabatic flame temperatures less than 2200 K. Such adiabatic flame temperatures can occur when firing lignite or high-moisture coals. For furnaces operated with the same thermal input at low efficiencies, the presence of wall deposits requires only a moderate increase in size.

A reduction of surface emissivities from 1 (clean "sooty" walls) to 0.4 (which is the lowest range reported for ash deposits (see Section 3) also causes a drop of η_f (Fig. 2). However, the required increase in size to maintain η_f is smaller than for the change of deposit surface temperatures from 700 K to 1300 K mentioned above. The size changes non-linear with changes of surface temperature but nearly linearly with ε_w between ε_w = 1 and ε_w = 0.5. Beyond ε_w = 0.2, L must increase non-linearly to maintain furnace efficiency.

When a deposit layer is formed, surface temperature is increased and wall emissivity decreased. However, the superposition of these effects on η_f is less than a pure summation; since, by decreasing ε_w, the net heat flux to the layer is reduced, thus retarding the increase of surface temperature to a certain extent.

3.0 AVAILABLE DATA OF THERMAL PROPERTIES OF ASH DEPOSITS AND DATA ANALYSIS

Thermal Conductivity. A comprehensive review of literature data for thermal conductivity k of ash deposits was published by Wall et al. (2). The thermal conductance, k, of the ash material increases reversibly with temperature until sintering or fusion occurs. At this stage, a rapid and irreversible increase of k is observed. Typical values of k for non-sintered deposits from Australian coals in actual furnaces vary between 0.1 10^{-3} KW/mK at 500 K up to 0.4 10^{-3} KW/mK at 1300 K. The factors contributing to the thermal conductance in the powdered deposits are: Conductance in the solid particles, gas conduction in the voids and radiative transfer through the voids. Fetters et al. recently measured k for boiler deposits of an Indiana coal (3) and point out that the dominant mode of heat trasfer through the deposit layer is by radiation at high temperature. The values of k measured for powdery deposits by Fetters et al. are about 2 times larger than those of

* 1m of furnace height corresponds to ≈ 500,000$.

Wall et al. (2) at the same temperature. This is contributed to the relative large particle sizes of the Indiana coal ash (75% in the 100μm range) compared to the Australian coal ash with mean weight particle diameters of 50μm and less.

Thermal conductivity of sintered and fused deposits found by the Australian researchers range from 0.5 10^{-3} KW/ mK at 800 K to 1.2 10^{-3} KW/mK at 1500 K. This is consistent with the recent findings of Fetters et al. (3) for crushed deposits from a boiler fired with Indiana coal and other literature values (4). The increase of thermal conductivity of sintered and fused deposits is due to a decrease of void space and increased transmissivity of the material. Assuming uniform mean conductivity, the thickness of a sintered deposit layer which maintains fusion at its surface can be estimated by

$$\Delta s_{fu} = \frac{k\,(T_{fu} - T_{t,a})}{\varepsilon_{\omega} q_{in} - \varepsilon_{\omega}\sigma T_{fu}^{4}} \qquad 2)$$

where T_{fu} is the ash fusion temperature, $T_{t,a}$ the temperature of the outer surface of the tubes and q_{in} the incident heat flux density. With typical values $k = 0.8\ 10^{-3}$ KW/mK, $T_{fu} = 1550$ K, $\varepsilon_w = 0.7$, $T_{t,a} = 750$ K and $q_{in} = 400$ KW/m^2 the layer thickness with a wet surface would be about 8 mm. Wall et al. emphasize that values of k obtained from ground deposits in laboratory studies are questionable since bounding of the deposit occurs in situ which leads to an increase of k. This agrees with our results for a 700 MW$_e$ boiler which yielded an overall value of k = 3.2 KW/m^{2}K for deposits which could not be removed by soot blowing (see Section 4).

Emissivity and Absorptivity

Reviews of emissivity data of ash deposits were given by Wall et al. (2) and recently by Becker (5). The literature data has a considerable spread of emissivity, between values of $\varepsilon_w = 0.9$ and $\varepsilon_w = 0.3$ depending on temperatures, ash origin and probe preparation. However, general agreement exists that, for non-sintered material ε_w decreases reversibly with surface temperature. After sintering, the emissivity changes irreversiblely to higher values (2). This agrees with measurements of furnace generated deposits of American coals carried out by Goetz et al. (6). These authors report values between 0.38 and 0.67 for powdery (initial) deposits, values between 0.76 and 0.93 for sintered deposits and values 0.65 and 0.85 for glassy and or molten deposits. The increase of emissivity with sintering and fusion is due to increased transmission of radiation into the surface of the deposit layer. In the range of surface temperatures of interest, namely between 800 K and 1400 K, measured total emissivities on probes of sintered real furnace deposits exhibit only slight variations with surface temperature (5), (6). However, measurements by Becker of spectral emissivities of deposits on laboratory prepared probes showed distinctive non-grey behavior. For typical flame temperatures of 1700 K and typical surface temperatures of 1100 K, up to 0.2 higher values were found for emissivities than for absorptivites. Non-greyness of emission and absorption is typical for glassy material and is due to the low spectral absorptivities at short wavelengthes which becomes dominant for radiative transfer at more elevated flame temperatures. The assumption of grey radiation of furnace deposits and consequent use of grey emissivity values for determination of absorption may lead to errors in heat transfer calculations for furnaces with moderate deposits since at lower surface temperatures absorption is several times larger than re-emission. By performing detailed one-dimensional spectral calculations, Becker showed that for a 10 m path length, typical of furnaces, and relatively cool walls errors up to +30% in predicted net heat flux densities would result from the assumption that the deposits were grey. However, these findings are based on spectral values found for laboratory prepared probes. Spectral measurements of real furnace deposits show reduced non-grey behavior (5), (6) and higher emissivities than the laboratory probes (6). Moreover, coloring agents such as unburnt carbon as well as the rough surface structure of real deposits and tube curvatures tend to make boiler surfaces more closely approximate grey behavior. Thus, the importance of non-grey deposits is uncertain in boiler chambers and, in any case, insufficient information is available to recommend replacing the assumption of grey radiation of deposits currently used in 3-D furnace models (see Section 4) by expensive more rigorous spectral models.

4.0 PREDICTIONS OF INFLUENCE OF WALL DEPOSITS ON HEAT TRANSFER IN EXISTING BOILERS

On the basis on the literature values of thermal properties discussed above a considerable number of performance predictions have been carried out for existing boiler combustion chambers in the past two years. Some results of those calculations with relevance to the impact of ash deposits on heat transfer follow. The tool used for the analysis is an extreme flexible 3-D Monte-Carlo type zone model (7), (8). In this model, the emissive power of each volume and surface zone is distributed into a discrete number of radiative beams. Taking multiple reflection at furnace walls into account, the beams are traced throughout the furnace volume until final absorption. Non-greyness of the combustion produts is modeled with a weighted grey gas approach. The radiating species considered are H_2O, CO_2 and particulates (soot, char and ash). Currently, char and ash particles are treated as grey radiators. The model of radiative exchange is directly coupled with a total heat balance of volume and surface (deposit) zones with unknown temperatures. The calculation of convective heat fluxes through the furnace is based on mass flow vectors at the boundary of each zone obtained from isothermal modeling. The heat release pattern is based on this flow field. The heat release due to volatile combustion is based on observed visible flame length and the heat release due to burnout of char particles is calculated from carbon and oxygen balances solved simultaneously with the heat balance.

Example 1: Tangentially Coal-Fired Boiler

This study was carried out to investigate the influence of ash deposits in a twin furnace of a boiler originally designed to fire No. 6 oil at a net thermal input of 1000 MW_t. However, the thermal input of the furnace was reduced to 590 MW_t to investigate the prospects of firing coal in this unit. The coal considered was a Utah coal with 8.8% ash content fired with 30% excess air. Figure 4 shows the zoning of the furnace and the assumed flow patterns. The heat release due to combustion is indicated by the shaded area. The surface conditions were specified by the following input data:

- Case A Clean surfaces, emissivity of tubes $\varepsilon_W = 0.9$
- Case B Powdery ash deposit, $\varepsilon_W = 0.6$, $\Delta s = 0.5mm$, $k = 0.3 \quad 10^{-3}$ KW/mK
- Case C Properties of ash deposit layer in upper part of the furnace (above heat-release zone) as specified for Case B; glassy ash deposit layer in lower part of the furnace with $\varepsilon_t = 0.8$, $\Delta s = 7mm$, $K = 1 \ 10^{-3}$ KW/mK.

The properties for the powdery (primary) and for the glassy (molten) deposit layer of the Cases B and C correspond to average data from literature as cited above. The actual calculations were carried out with an effective emissivity of the tube walls taking the shadow effect of the gap between adjacent tubes into account.

Table 1 and Figures 5 through 7 show that the build-up of ash deposits seriously affects overall and local heat transfer. The difference ($\Delta\eta_f$) in computed furnace efficiencies for the extreme cases, A (clean walls) and C (highest thermal resistance), is 6.2 percentage points. The formation of a first initial deposit layer (Case B) has a stronger impact on heat transfer than subsequent increase of deposits in the lower furnace (Case C). The increase of the thickness of ash deposit opposite to the heat release zone displaces the peak heat fluxes up into the regions of the thinner deposits (Fig. 6). This is one reason why the build up of deposit layers, once started, spreads into adjacent wall zones. Once the deposit layers begin growing, surface temperatures can soon reach values in the range between softening (1400 K) and fusion temperature (1500 K) as indicated by shaded areas in Fig. 7. The furnace model is also able to predict, for a given coal ash fusion temperature approximately the development and extent of molten slag layers.

Another investigation showed for the same boiler fired with COM at a rate of 875 MW_t, showed that a decrease of surface emissivity from 0.9 (clean) to 0.6 (initial deposit) raised mean furnace exit temperature by 55 K.

Example 2 Opposed P.F. Fired Boiler

This study was carried out in order to verify the 3-D furnace heat transfer model with performance data available from a coal-fired, boiler combustion chamber of 1732 MW_t fuel heat input. The coal had a medium volatile content, an ash content of 6.6%, and was fired with 28% excess air. In this case, the flow pattern was based on detailed distribution of mass mean flow vectors measured in a physical isothermal model. However, turbulent components were superimposed on these vectors with the help of a simple model of turbulence. Fig. 8 shows a comparison of the profiles of gas temperatures measured and predicted for 100% Load in one half of the furnace outlet plane. The difference between predicted and measured values was less than 25 K. The good agreement is partially due to a reasonable assumption of the effective heat conduction coefficient $(k/\Delta s)_{eff}$ of the deposit layers. Fig. 9 shows how the predicted mean furnace exit temperature varied with (k/Δ

$s)_{eff}$ and compares those predictions with two data points obtained from measured heat balances of the boiler immediately after soot blowing and 20 h after soot blowing. Since measurements and observations yielded approximately a 2mm deposit layer, which could not be removed by soot blowing an effective thermal conductivity of 3.2 10^{-3} /mK can be deduced. An assumed value of k = 0.8 10^{-3} KW/mK for a dry partially sintered deposit would suggest the build-up of an additional layer of 1.5 mm, 20 h after soot blowing for a total layer of 3.5 mm thickness.

Fig. 9 also contains the relationship of $T_{ex} = f(k/\Delta s)$ for a similar boiler of 1250 MW_t heat input in which slagging and fouling problems are encountered. Further applications of the 3-D furnace model with respect to impact of wall deposits on heat transfer in CWM and COM fired furnaces may be found in (5), (10).

5.0 CONCLUSIONS

Thermal conductivity and emissivity of wall deposits have a considerable effect on heat transfer in large boilers. This results in temperature differences of furnace exit temperatures which influence furnace height, performance and costs. More exact values of deposit thermal properites, which vary over a wide range of temperatures and conditions, than currently available are needed for detailed prediction of the initial formation of deposit layers. However, gross characteristics of thermal properties can be assumed and are sufficient to estimate the performance of furnaces, since the model contains other major uncertainties such as, thickness and inhomogenous distribution of deposits at furnace walls and superheaters. This is especially true between soot blowing cycles. The 3-D heat-transfer model used in the present study has the potential to form the basis of a more comprehensive model of slagging and fouling because it can provide reliable predictions of flame and deposit temperatures. A model of ash transport is currently being coupled with the furnace heat transfer model which will account for time-temperature histories of ash and wall collisions.

6.0 LITERATURE

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Table 1. Thermal Performance of 590 MW_t Coal-Fired Combustion Chamber For Various Slagging And Fouling Conditions

No.	Case	Furnace Efficiency	Mean Furnace Exit Temper-ature	Mean Net Heat Flux Density	Max. Net Heat Flux Density	Vertical Position of Max. Net Heat Flux Density	Max. Flame Temp.	Max. Furnace Exit Temp.	Unburnt C_{fix}	Carbon Content of Fly Ash
		%	K	KW/m^2	KW/m^2	m	K	K	%	%
A	Clean Surfaces	40.3	1436	168	304	14.9	1661	1515	1.35	6.43
B	Powdery Ash Deposit	35.6	1519	148	235	16.7	1728	1582	0.89	4.33
C	Slagging Lower Half	34.1	1541	143	239	19.2	1776	1610	0.75	3.68

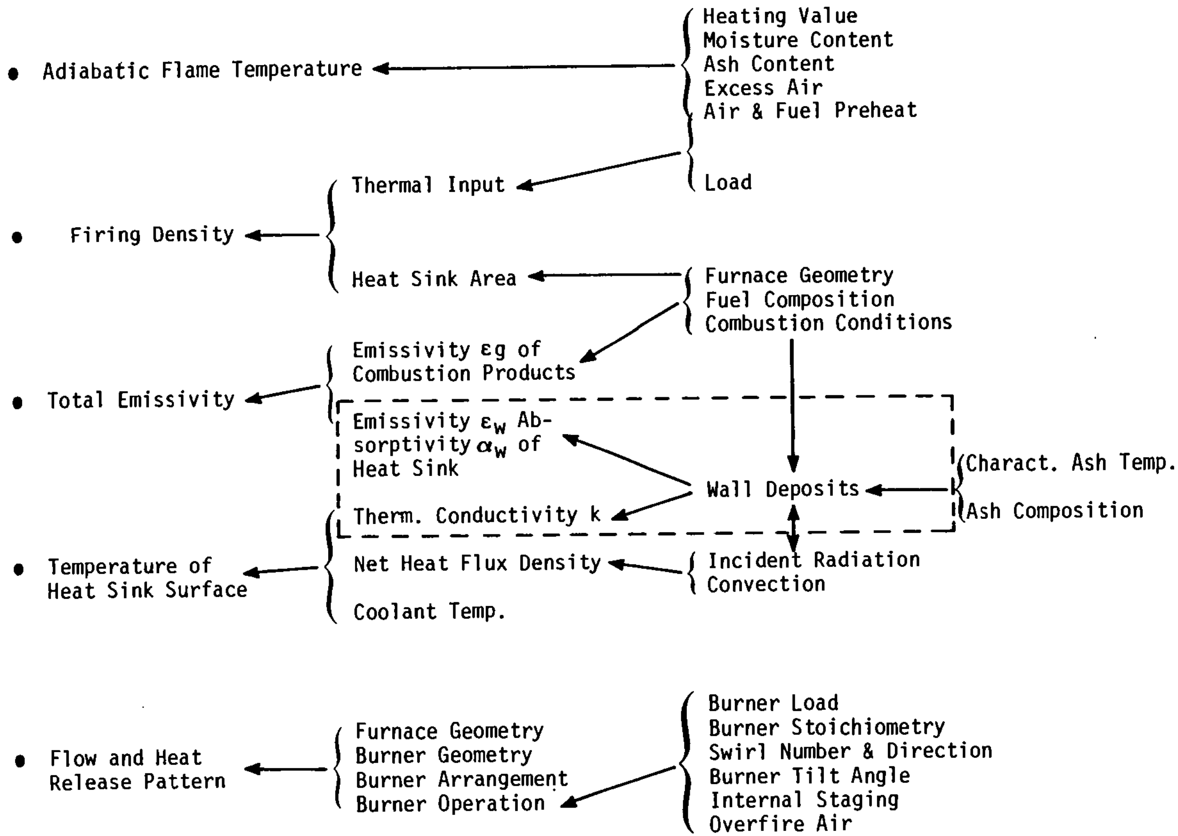

Figure 1. Major Factors Influencing Thermal Performance of Furnaces

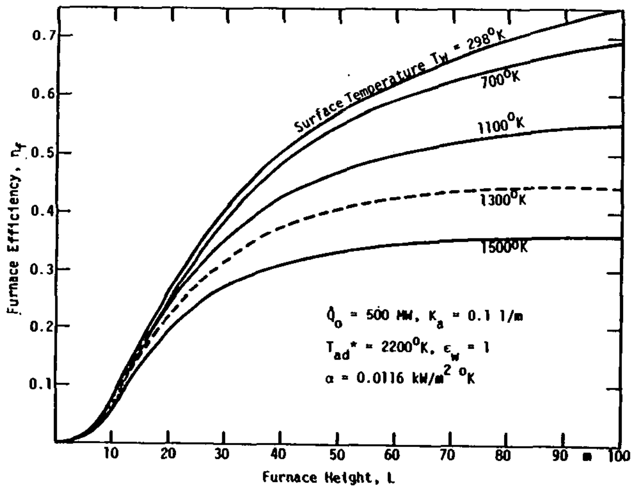

Figure 2. Dependency of Furnace Efficiency on Furnace Dimensions for Various Surface Temperatures.

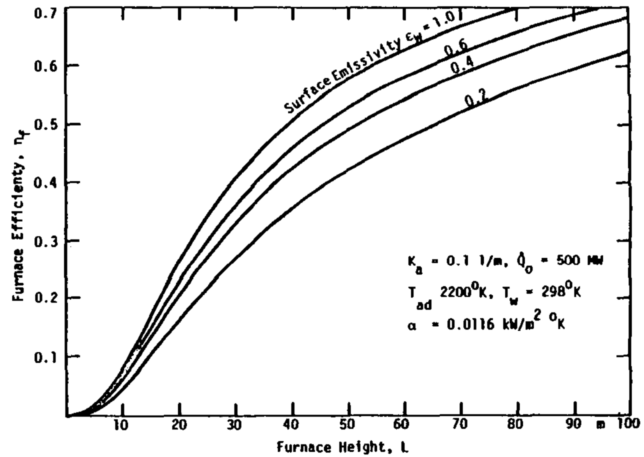

Figure 3. Dependency of Furnace Efficiency on Furnace Height With Surface Emissivity as Parameter.

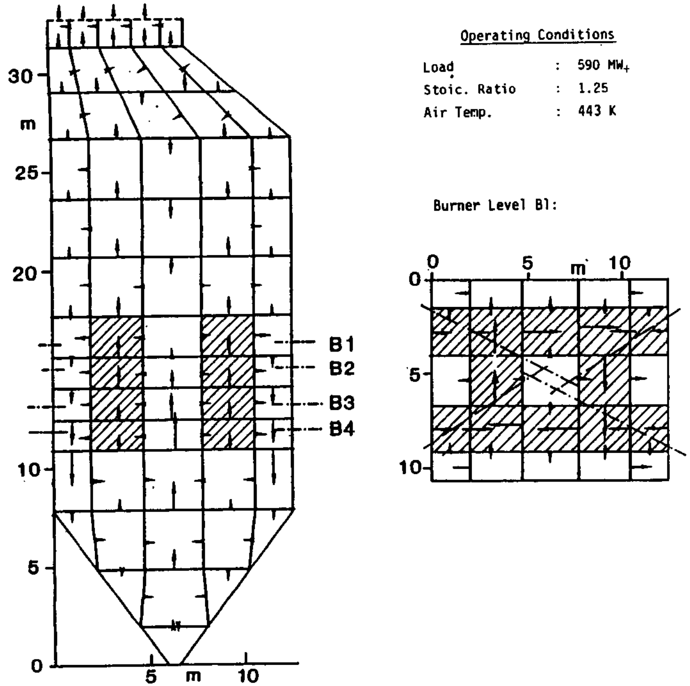

Figure 4. Geometry and Zoning of Tangentially Fired Boiler Originally Designed for Oil Firing with 1000 MW_t Thermal Input.

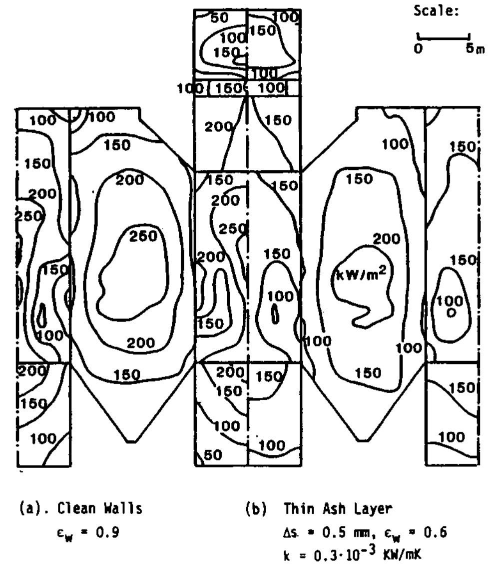

Figure 5. Influence of Wall Deposits on Predicted Net Heat Flux Distribution in Boiler Combustion Chamber Fired with Coal at a Rate of 590 MW_t.

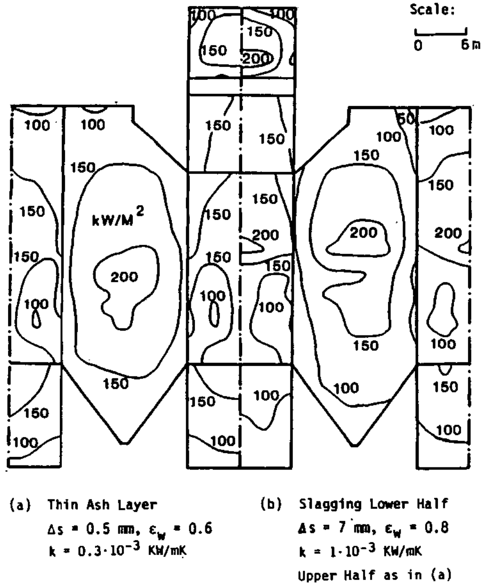

Figure 6. Influence of Slagging in Lower Furnace Half on Predicted Net Heat Flux Distribution in Boiler Combustion Chamber Fired with Coal at a Rate of 590 MW_t.

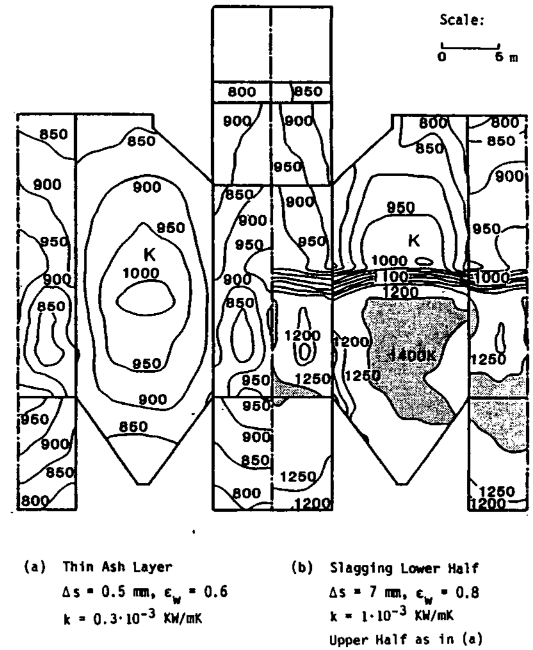

Figure 7. Influence of Slagging in Lower Furnace Half on Predicted Surface Temperatures of Deposits in Boiler Combustion Chamber Fired with Coal at a Rate of 590 MW_t.

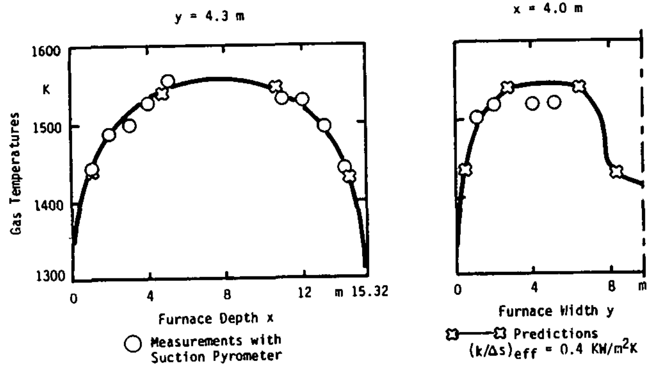

Figure 8. Comparison of Temperature Profiles Predicted and Measured Near Furnace Exit (z = 68.6 m) of 1730 MW_t Opposed Coal- Fired Boiler Combustion Chamber.

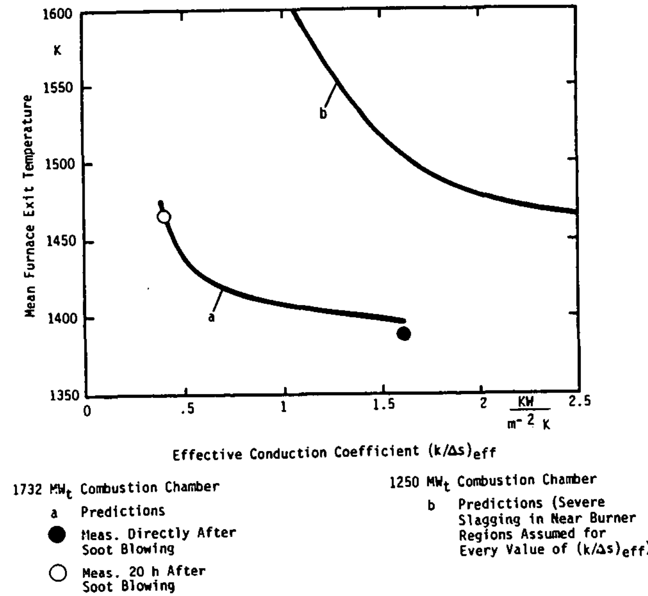

Figure 9. Dependance of Mean Furnace Exit Temperature on Effective Conduction Coefficient for Two Opposed Coal-Fired Boiler Combustion Chambers.